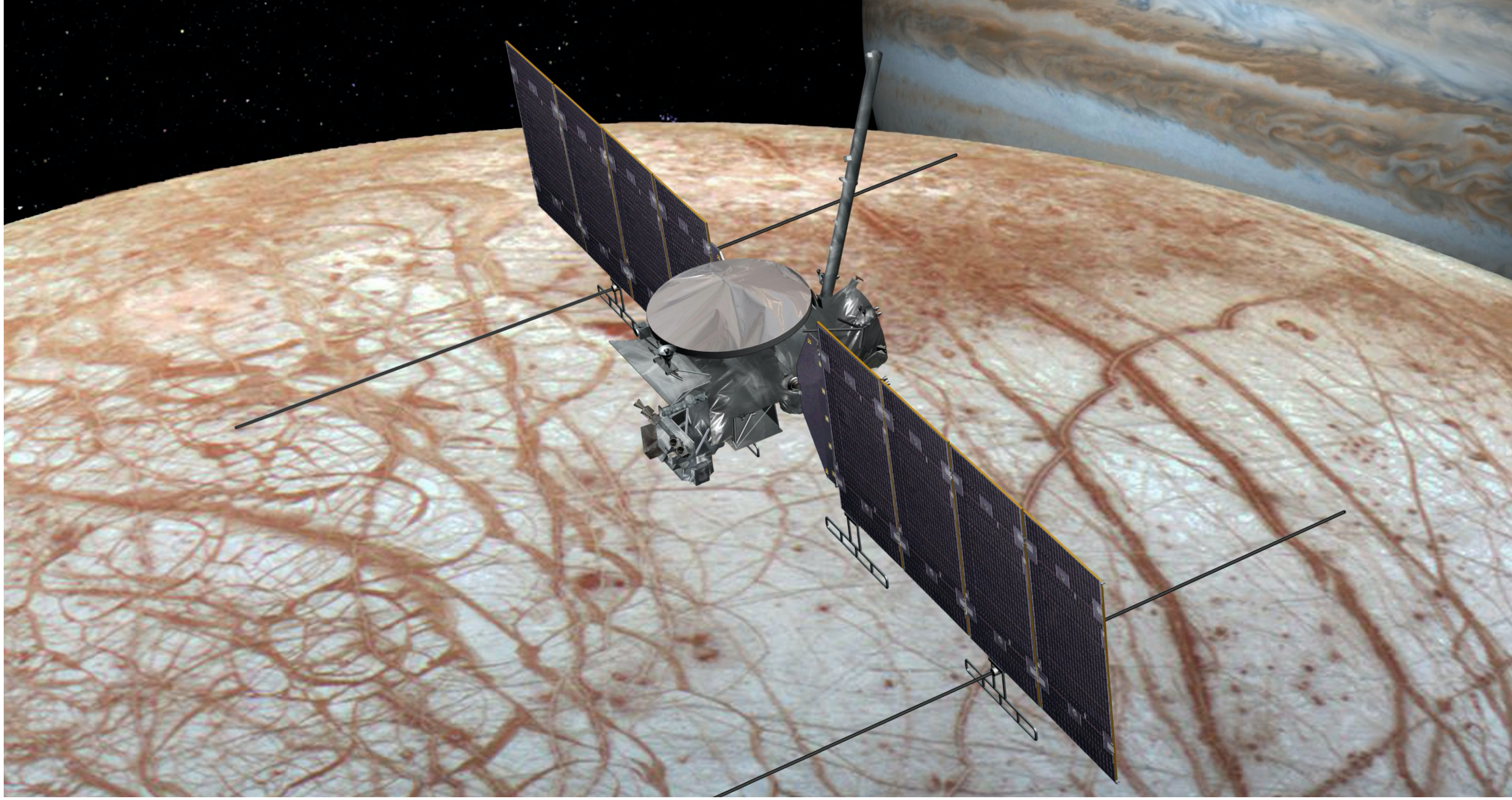


Orbit Determination Sensitivity Analysis for the Europa Clipper Mission Tour

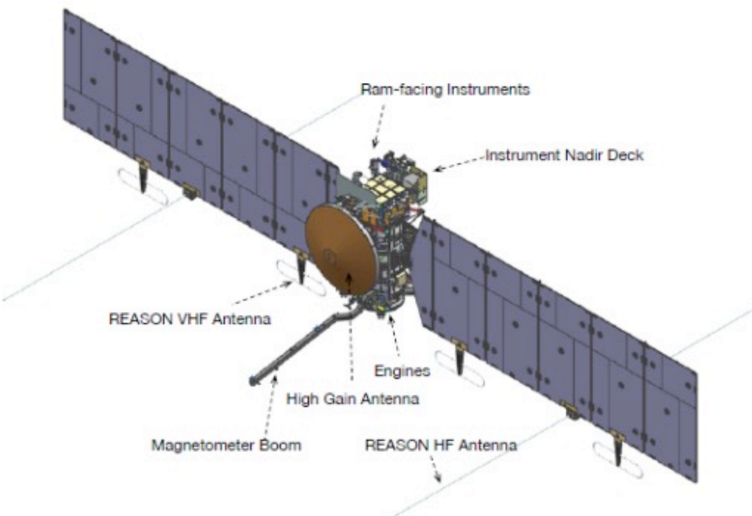
Zahi Tarzi, Dylan Boone, Sumita Nandi
Nickolaos Mastrodemos, Brian Young

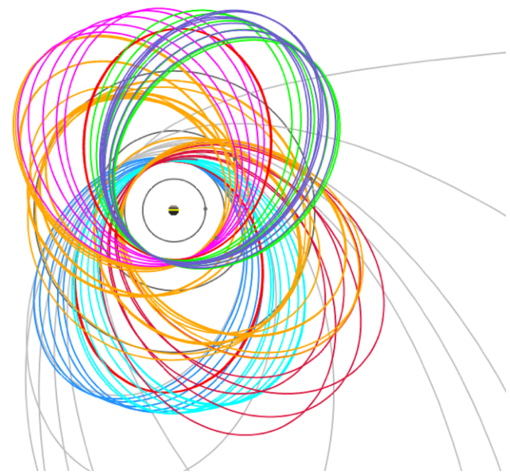
Jet Propulsion Laboratory
California Institute of Technology

29th AAS/AIAA Space Flight Mechanics Meeting
January 13-17, 2019 Ka'anapali, Hawaii

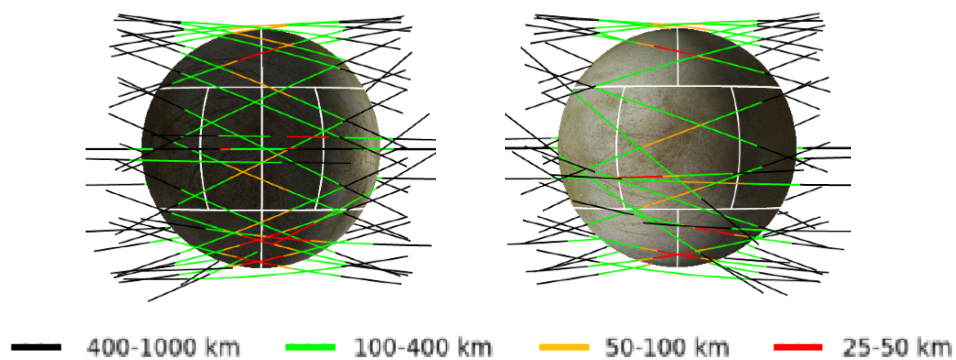
Introduction

Europa Clipper will explore Europa and investigate its habitability utilizing a set of five remote sensing instruments, four *in-situ* instruments, radar, and a gravity science investigation.





2022* launch direct to Jupiter
2024 arrival to Jupiter system
46 Europa flybys over 3.7 years
4 Ganymede and 9 Callisto flybys
4:1 resonant orbit with Europa
14 days between Europa Encounters



*Since updated to 2023

Navigation Strategy

Navigation Goals:

- Return the spacecraft to a reference trajectory at the time of targeted flybys (Delivery)
- Meet predicted spacecraft ephemeris uncertainty levels required to accurately point instruments during flybys (Knowledge)
- Meet reconstructed spacecraft ephemeris uncertainty levels required to accurately update instrument pointing post-flyby (Reconstruction)

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The Europa Clipper Mission baseline navigation plan meets all current ephemeris uncertainty requirements.

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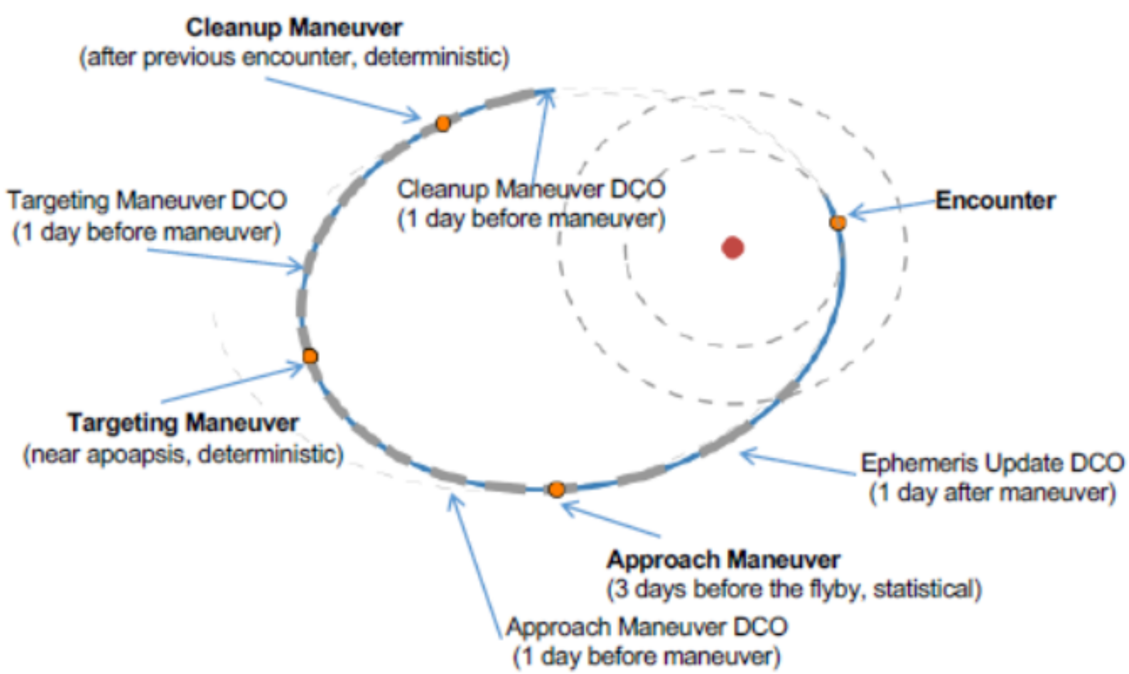
Sensitivity Study Goal:

- Investigate variations to the navigation assumptions in order to measure and improve the robustness of the current navigation plan

Navigation Architecture

- Each transfer from encounter to encounter is referred to as an arc
- Each arc usually has 3 maneuvers: 2 deterministic, 1 statistical



Orbit Determination

Tracking Data Assumptions

Radiometric Data

- 2-way Doppler and range collected every other 8 hour pass
- No data from 24 hours prior to 12 hour after Europa flybys
- Nominal data cutoff (DCO) for maneuver design is 1 day before execution time

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Investigated use of Narrow Angle Camera (NAC) instrument to obtain Europa images to augment radiometric data

Optical Data*

- 16 Europa images taken over a 2 hour window
- Observations located 2 days before (for knowledge update delivery) and 2 days after (for reconstruction delivery) each Europa encounter.

*Non-baseline

Orbit Determination

Filter Parameters

A covariance analysis is used to predict the expected uncertainty in the spacecraft ephemeris given errors in dynamical models, tracking data schedule, and tracking data errors.

Simulated tracking data are processed in an epoch state least squares navigation filter to compute the expected spacecraft state and parameterized model uncertainties:

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Estimated

- State position & velocity
- Maneuver execution
- Jupiter/Satellite ephemeris & GM, Jupiter harmonics & pole
- Reaction wheel desaturation impulses via thrusters (“wheel biasing”)
- Uncorrelated stochastic accelerations

Considered

- Earth polar motion
- Clock bias
- DSN station locations
- Troposphere/Ionosphere path delay

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The estimated satellite covariance in each arc is mapped forward to next arc epoch and used as a new a priori.
A lower limit (floor) of 250m is placed on the estimated uncertainty to avoid unrealistically low uncertainty from many repeated observations

Maneuver Design

Monte Carlo Analysis

A linear Monte Carlo analysis is used to compute ΔV statistics and maneuver dispersions as an input to the OD covariance study.

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    - Errors modeled parametrically with fixed and proportional components due to magnitude and pointing errors.

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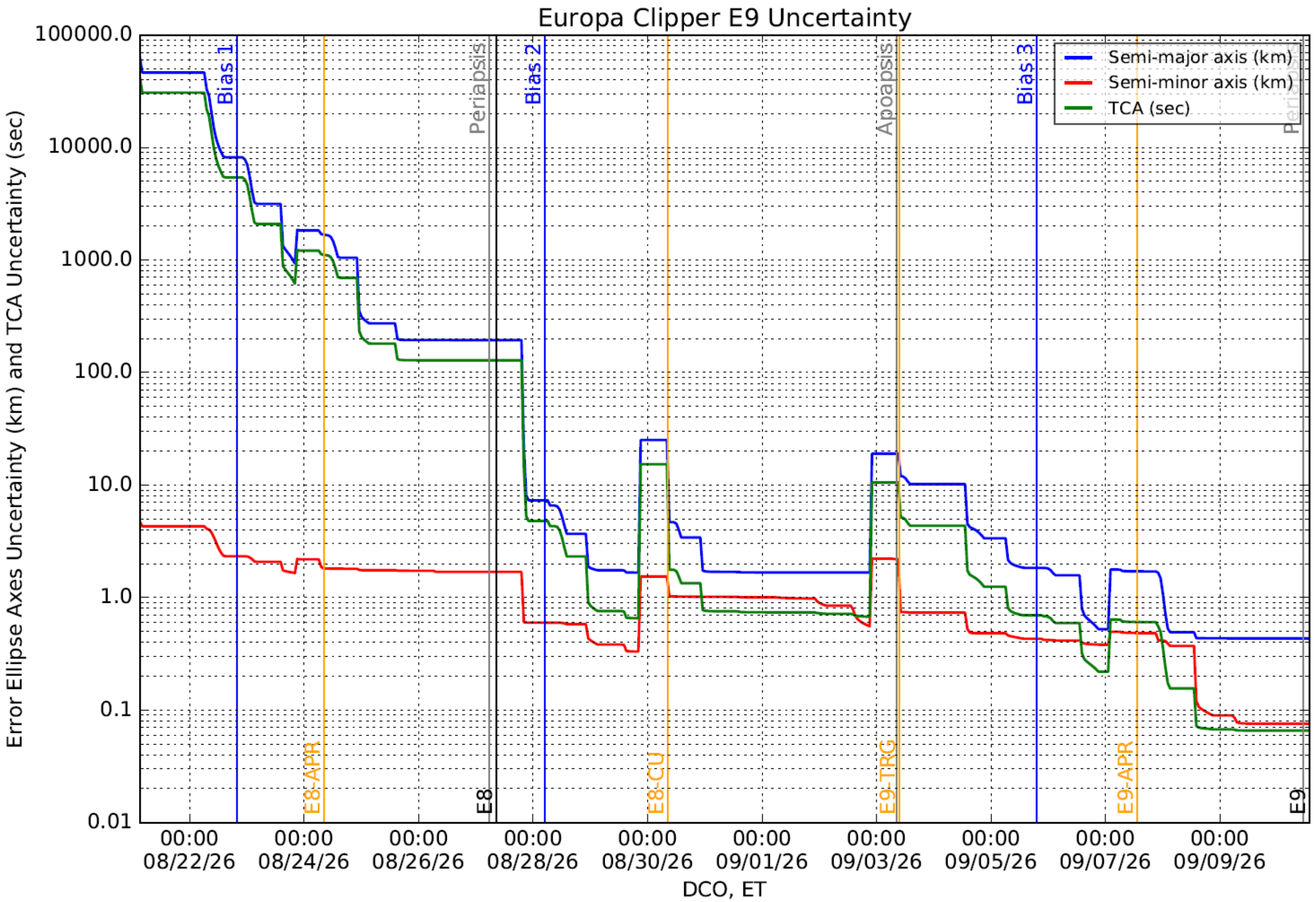
Telemetry Update

- Engine model parameters and expected telemetry data assumptions are used to derive expected reconstructed maneuver pointing accuracy
- Assists in reconstructing maneuvers by constraining components of maneuver covariance transverse to the burn direction.
- Results in smaller expected reconstructed accuracy than using radiometric tracking alone for maneuvers > 50 mm/s

B-plane Uncertainty History (E9)

No Maneuver Pointing Telemetry



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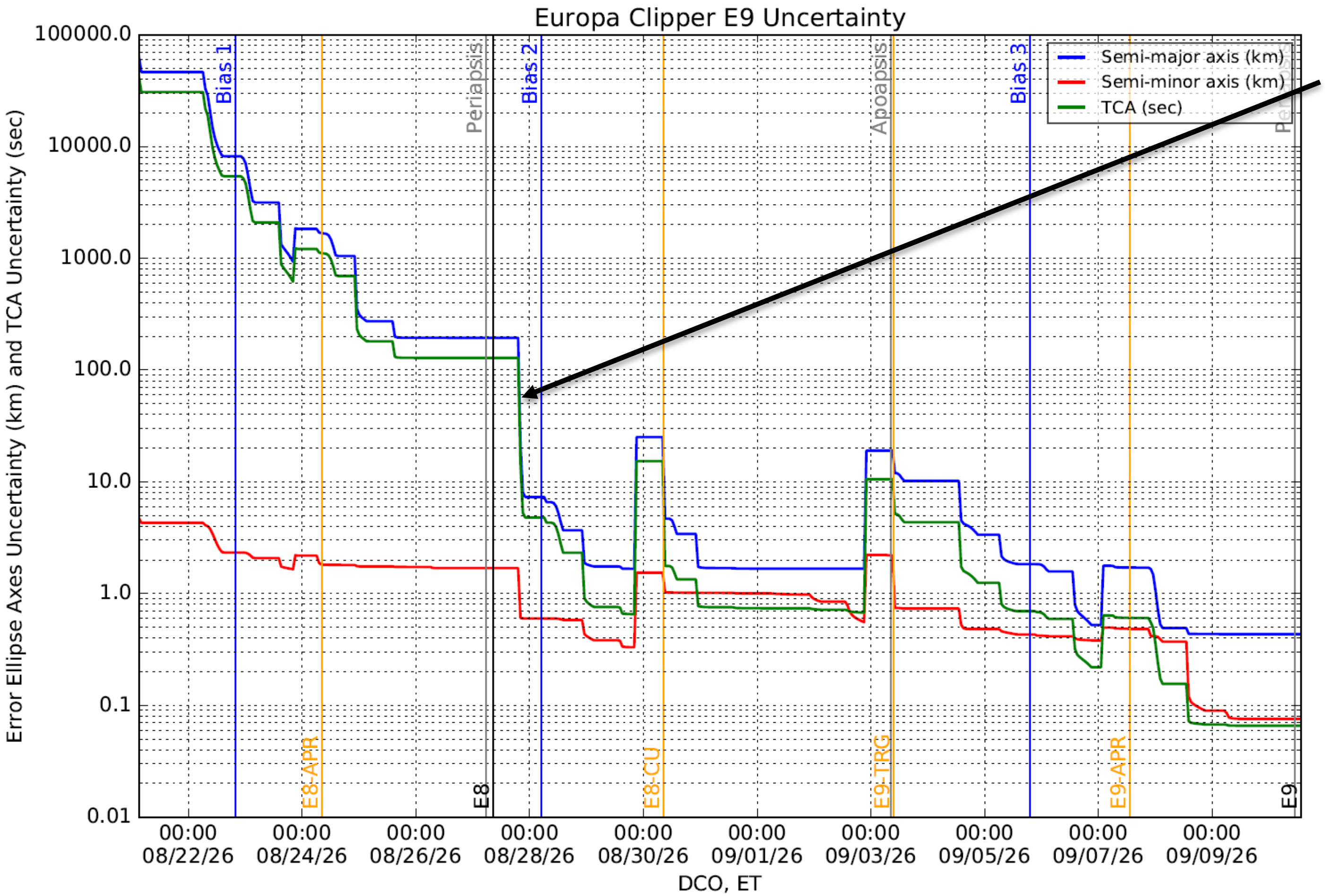

Drop-off in uncertainty after post-flyby tracking is received.

B-plane Uncertainty History (E9)

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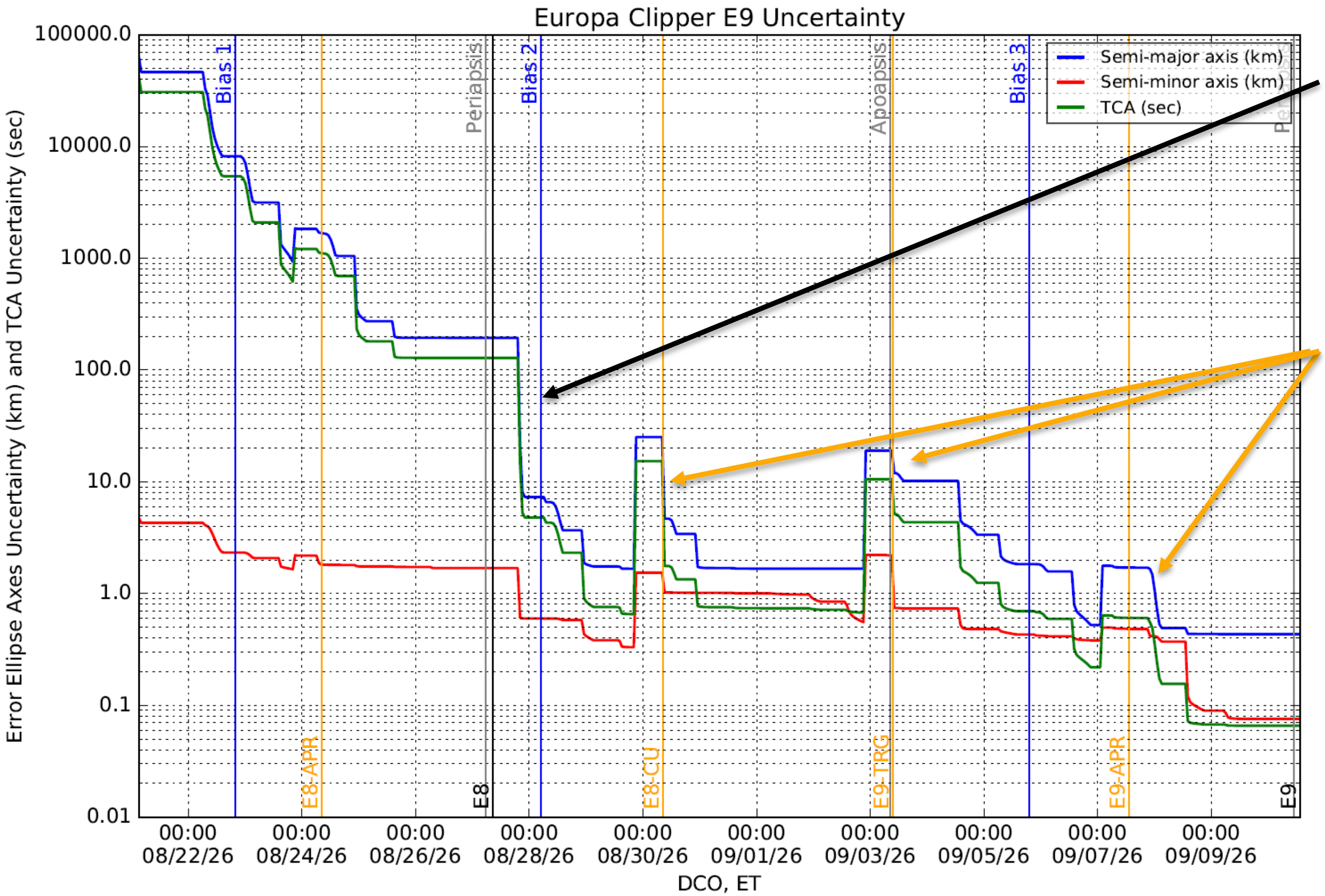
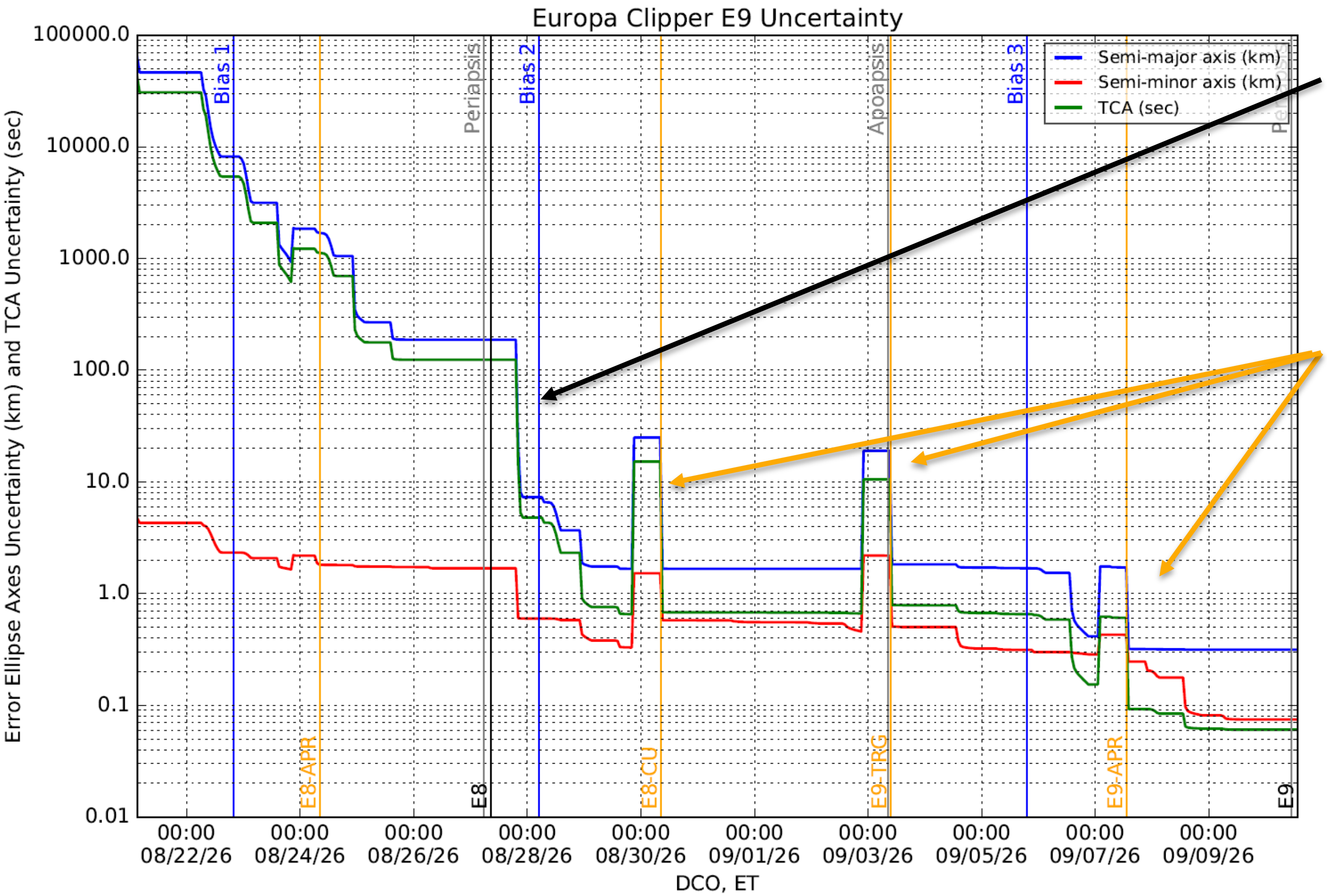


Drop-off in uncertainty after post-flyby tracking is received.

Uncertainties spike due to maneuver execution errors (delivery), then fall off again after tracking data received (knowledge).

B-plane Uncertainty History (E9)

With Maneuver Pointing Telemetry

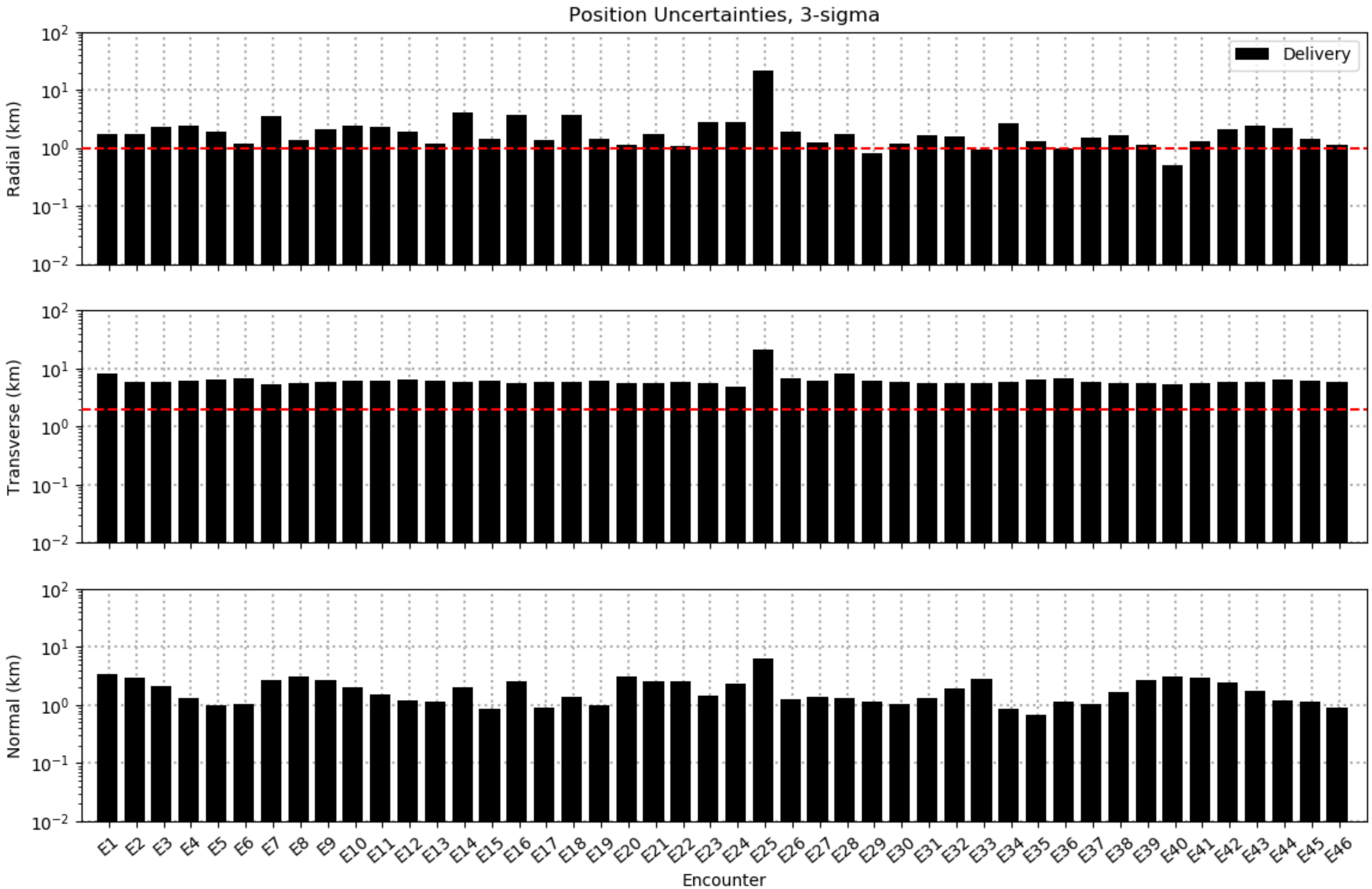


Drop-off in uncertainty after post-flyby tracking is received.

Steeper drop-off in uncertainties post-maneuver with the addition of pointing telemetry

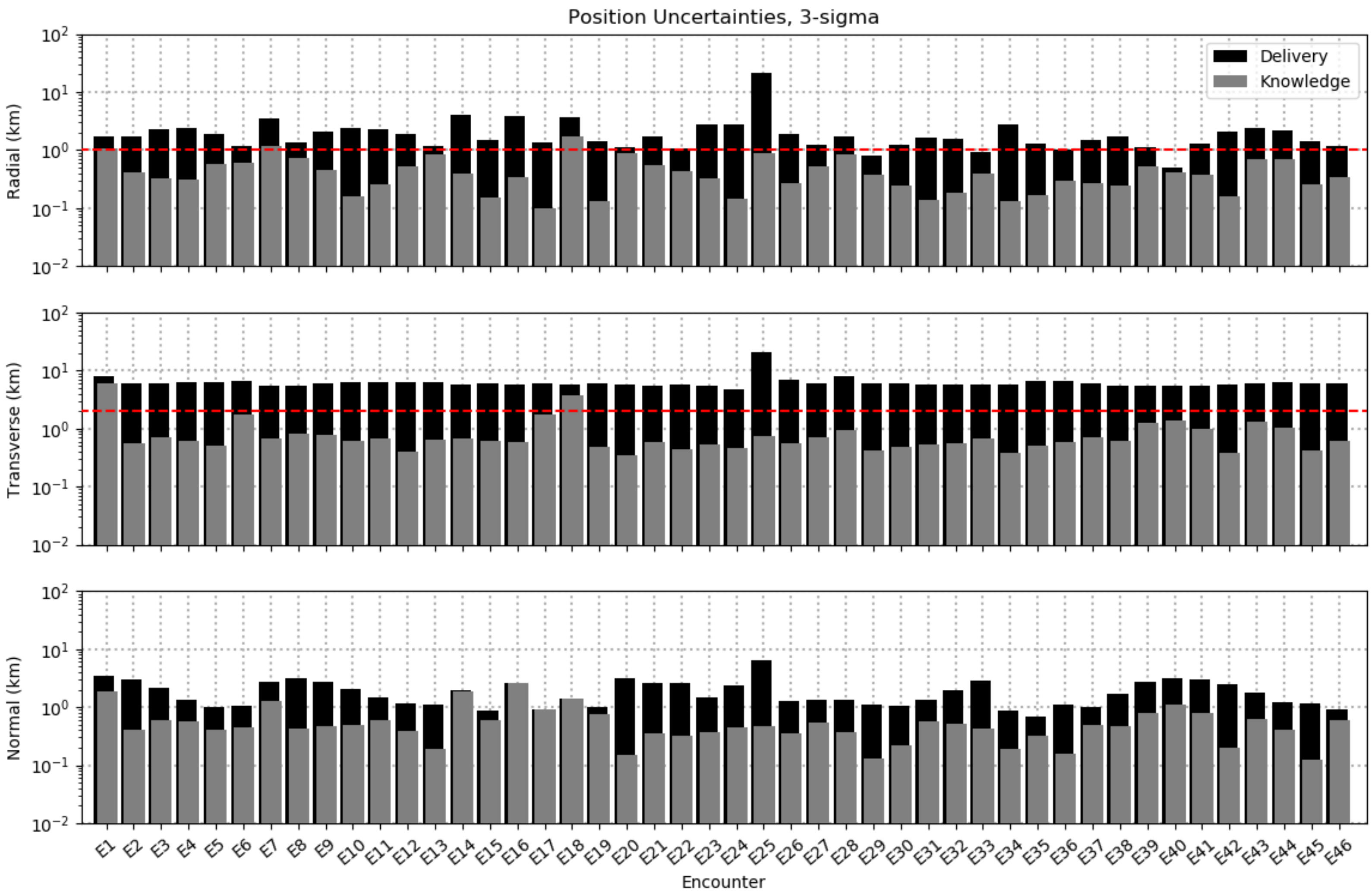
Europa Encounter Results

Encounter Delivery Uncertainties in RTN Coordinates (3σ)



Europa Encounter Results

Knowledge Update Uncertainties in RTN Coordinates (3σ)



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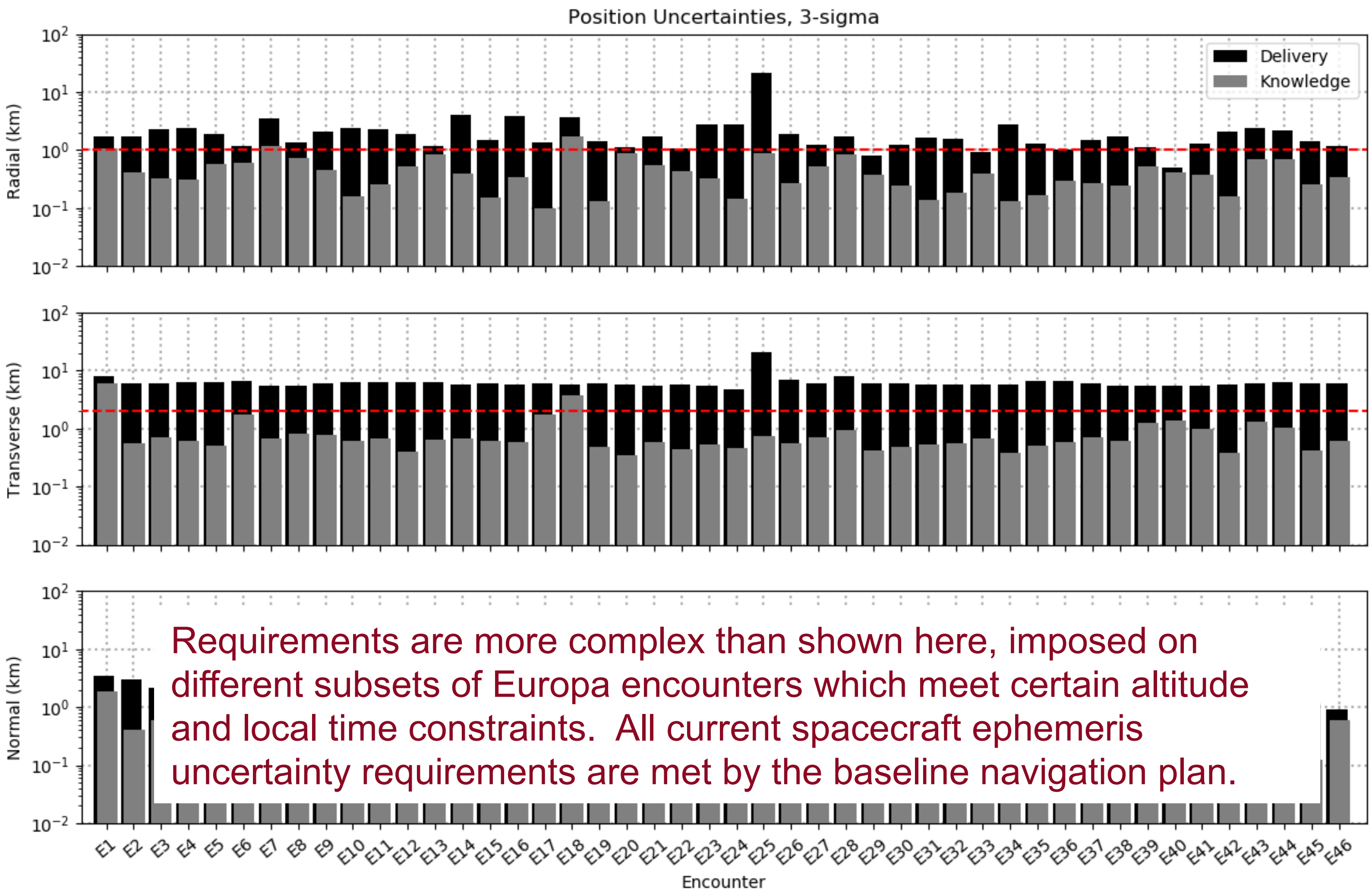

Requirements are more complex than shown here, imposed on different subsets of Europa encounters which meet certain altitude and local time constraints. All current spacecraft ephemeris uncertainty requirements are met by the baseline navigation plan.

OD Parameter Variations

Variations on Tracking Data

Case	Description
Doppler Only	Only Doppler data, no range
Continuous Tracking	Continuous doppler/range during the tour, excluding occultations and Encounters
Data Weights 0.1x/10x	Increase/reduce the Doppler and range data weights by a factor of 10
No Telem	No maneuver pointing telemetry available
Capability Telem	Improved 'Capability' level of telemetry available - without GNC margins
TRG mnvrs DCOs-2days	DCO for targeting maneuvers is moved back to 2 days before maneuver execution
All mnvrs DCOs-2days	DCO for all maneuvers is moved back to 2 days before maneuver execution
Flyby Data*	2 hours of de-weighted (10x) doppler data centered at Europa Encounter (Excl: E28,E32,E39,E43)
OpNav Data*	Optical data used, details presented previously

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Flyby Data*	2 hours of de-weighted (10x) doppler data centered at Europa Encounter (Excl: E28,E32,E39,E43)
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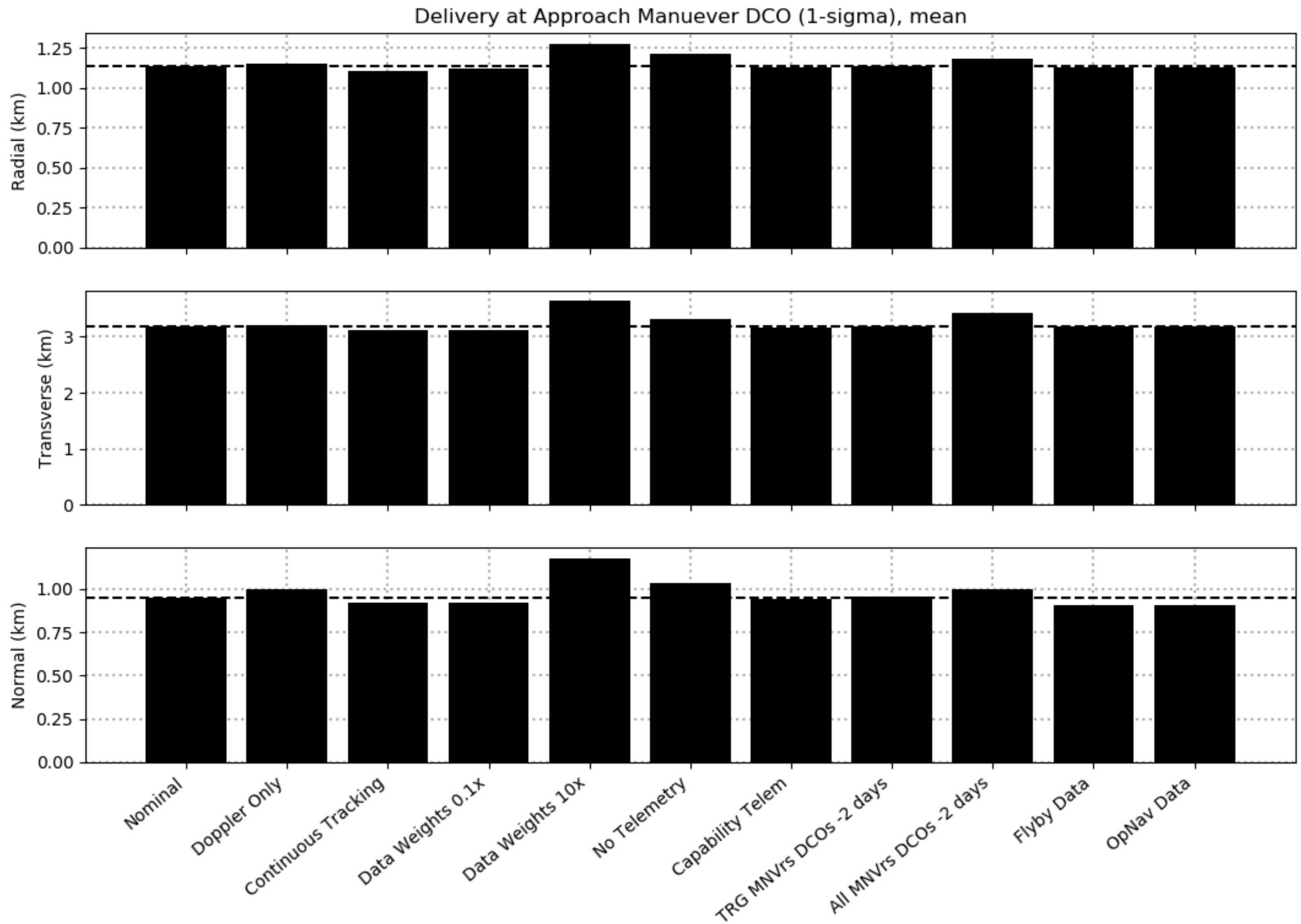
Variations on Dynamic Parameters

Case	Description
Maneuver Execution Errors 0.5x/2x	Increase/reduce the maneuver exeucution gates errors by a factor of 2
Sat Floor 0.5x/2x	Increase/reduce the satellite position knowledge floor by a factor of 2
Stochastics 2x/10x	Increase the background stochastic acceleration error by a factor of 2/10
Wheel Bias 2x/10x	Increase the error level associated with wheel biases by a factor of 2/10

*Non-baseline

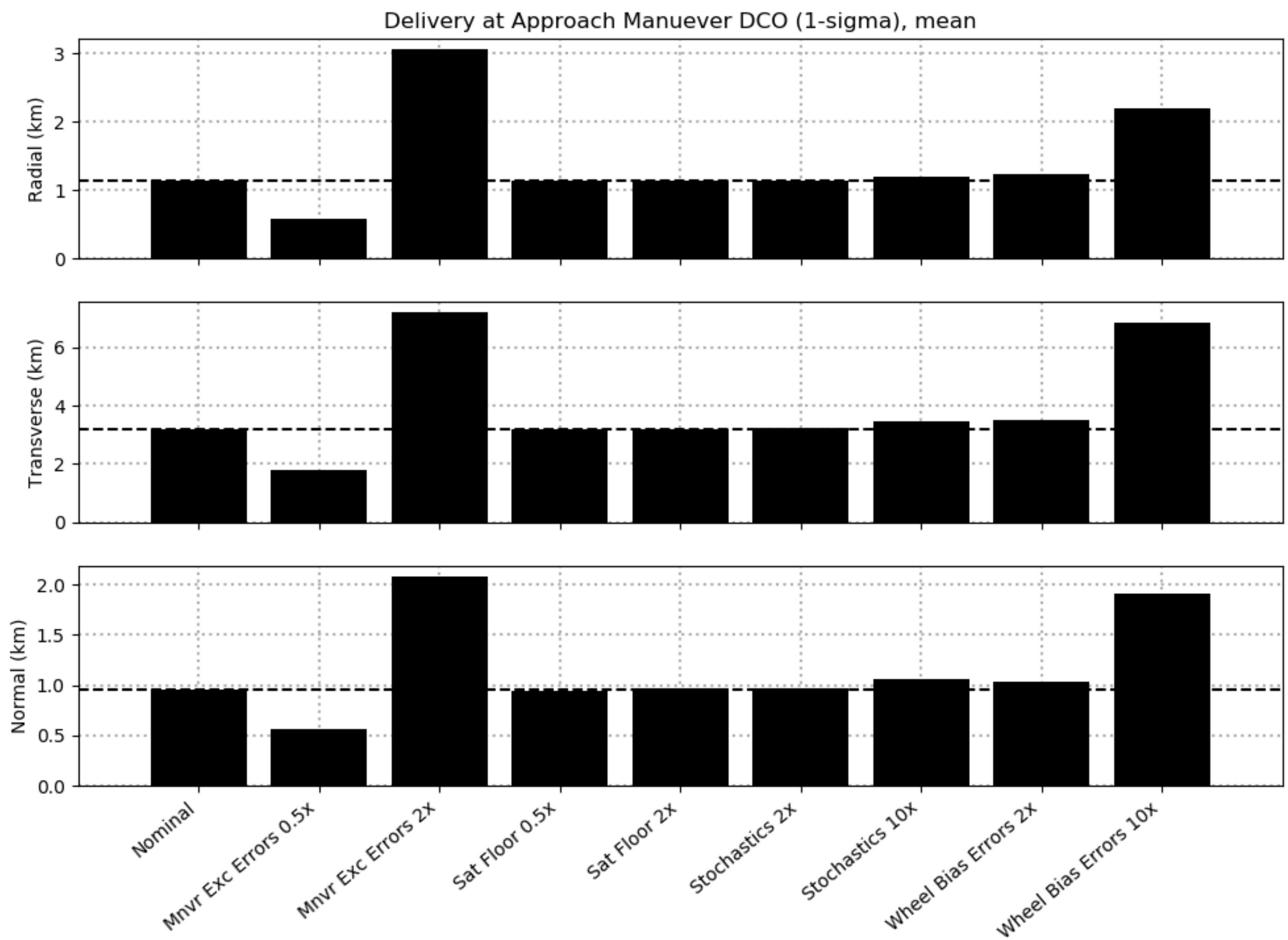
Mean Delivery Uncertainties

Variations on Data Type and Amount



Mean Delivery Uncertainties

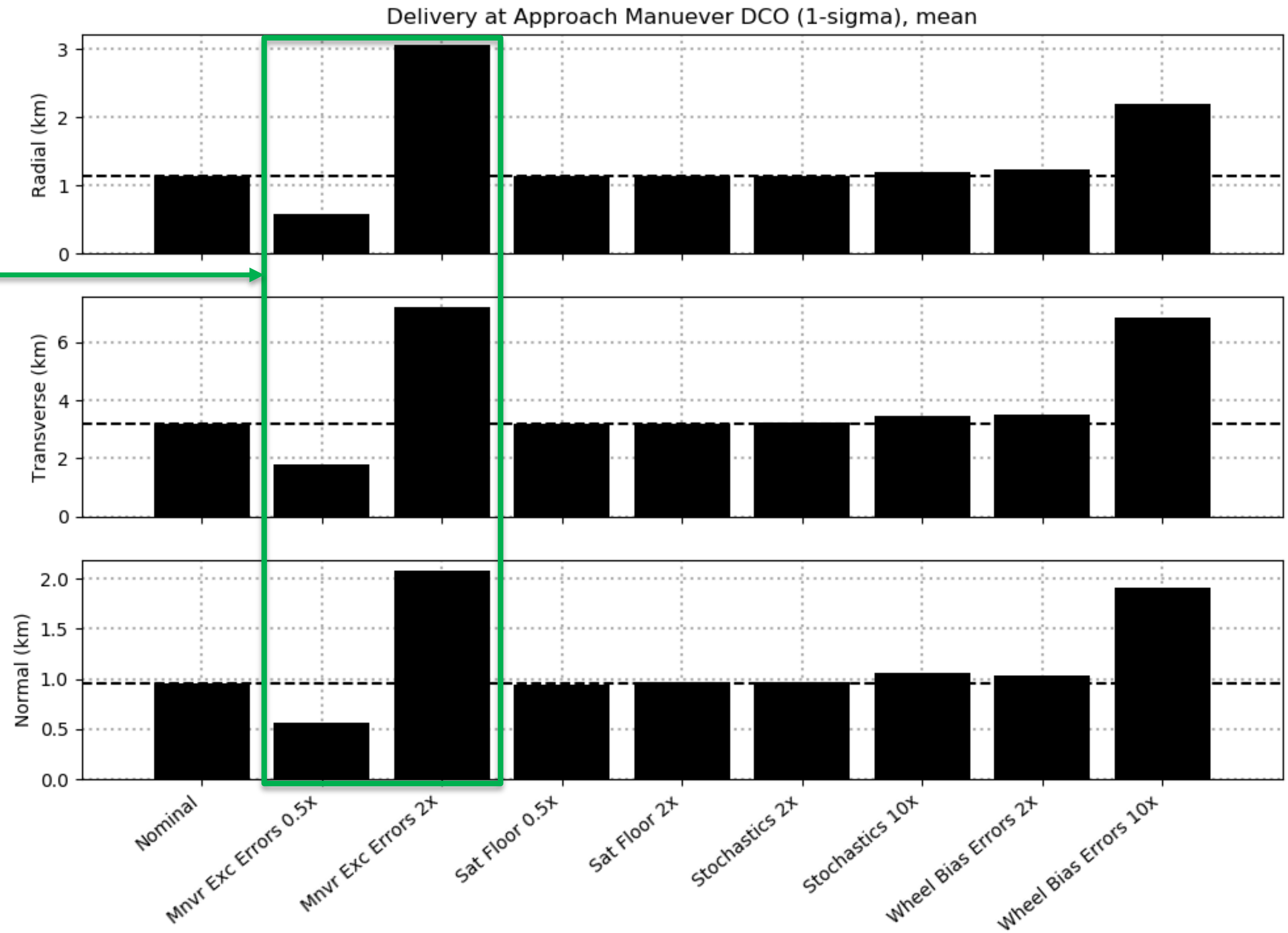
Variations on Dynamic Parameters



Mean Delivery Uncertainties

Variations on Dynamic Parameters

Large impact from changing the maneuver execution errors

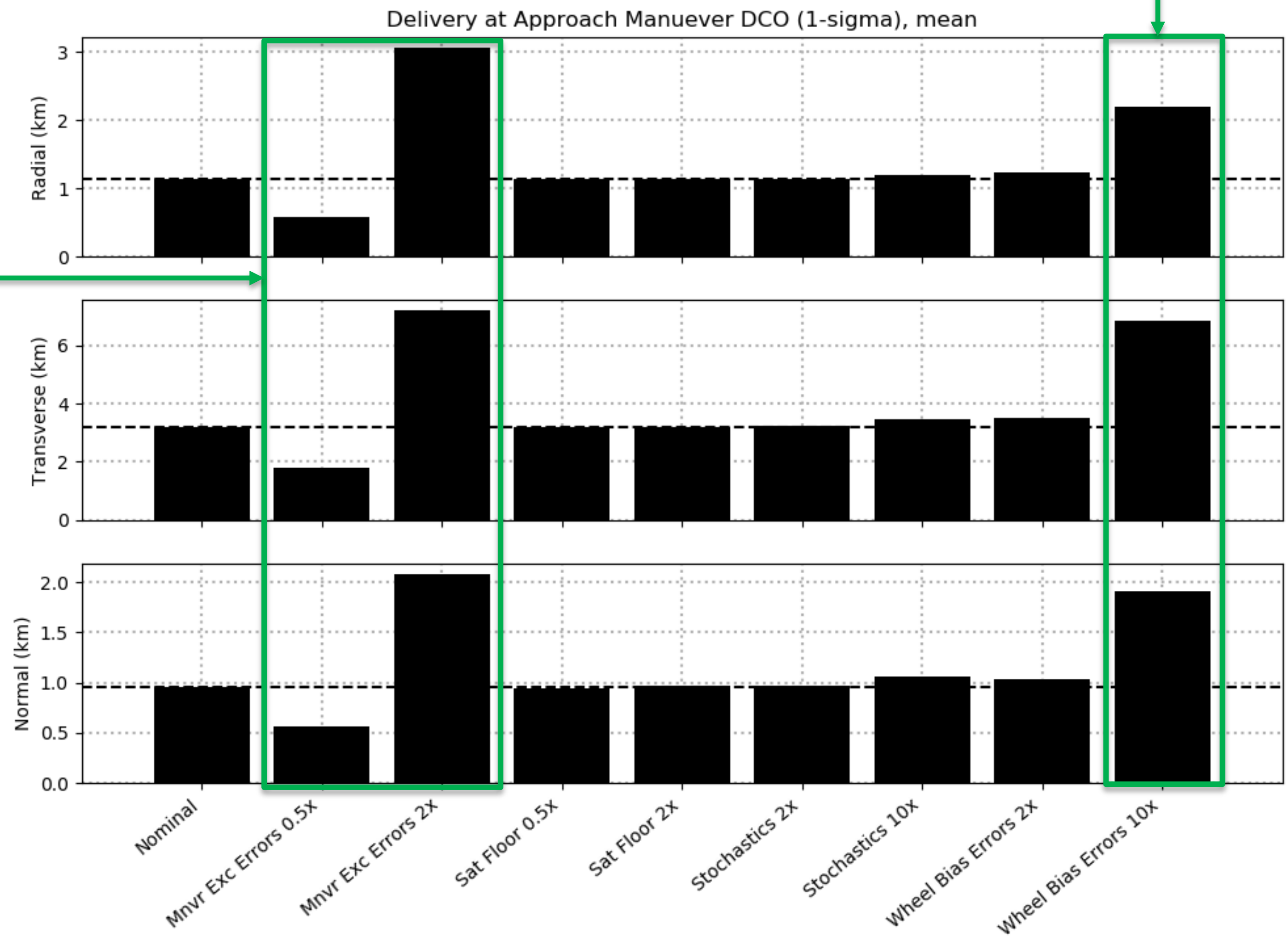


Mean Delivery Uncertainties

Variations on Dynamic Parameters

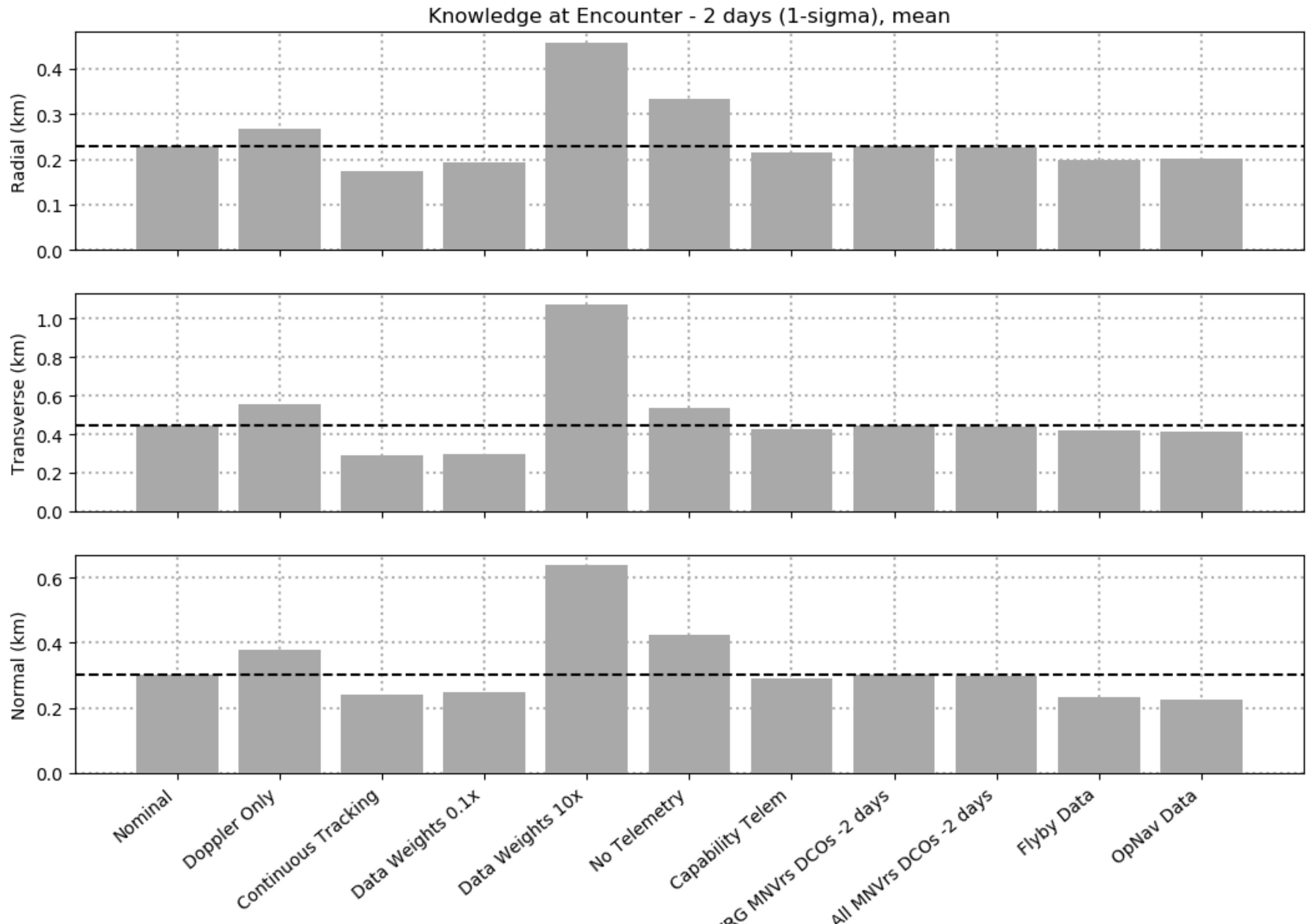
High uncertainties seen from increasing wheel biases by 10x

Large impact from changing the maneuver execution errors



Mean Knowledge Uncertainties

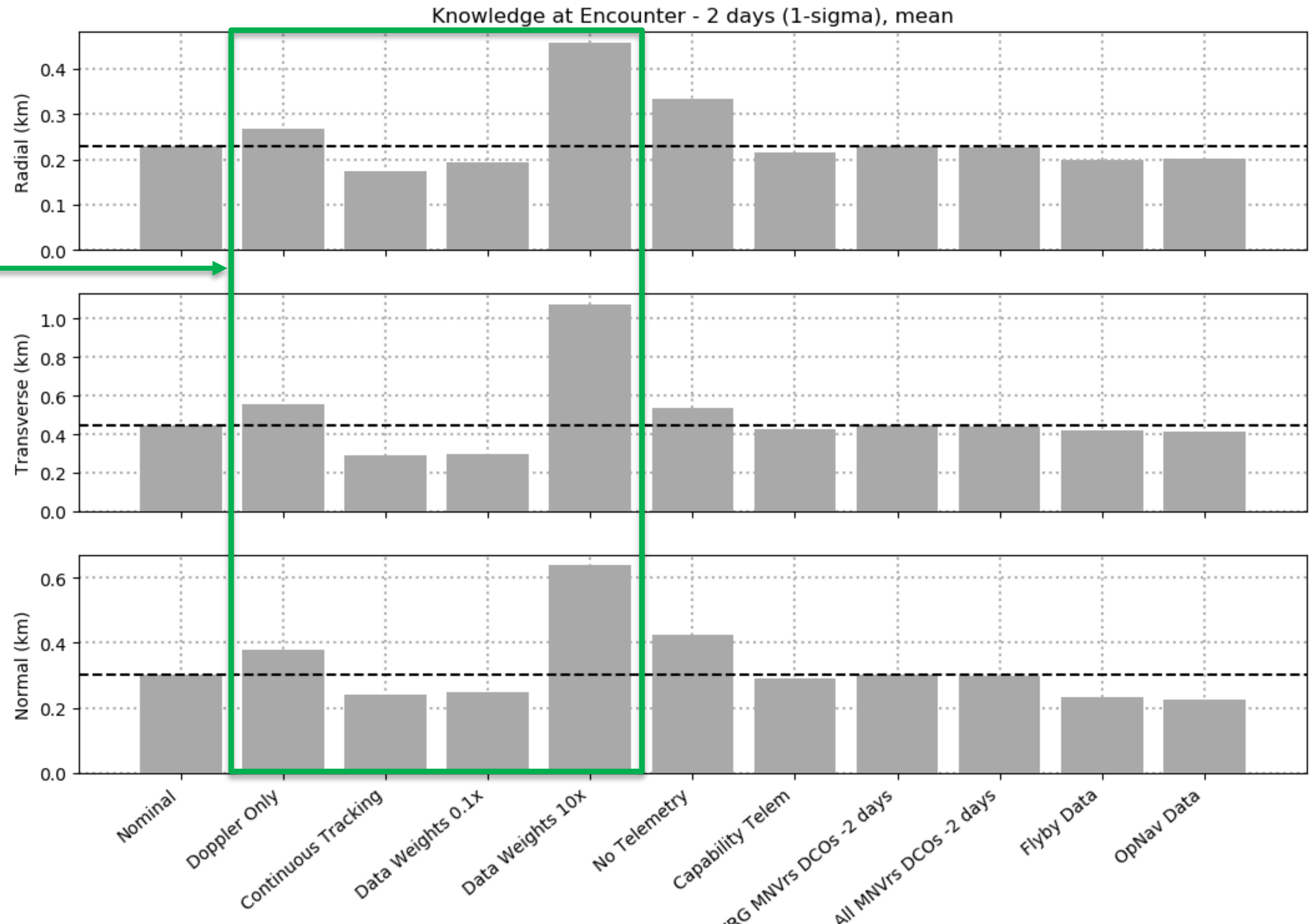
Variations on Data Type and Amount



Mean Knowledge Uncertainties

Variations on Data Type and Amount

Some sensitivity to quality and quantity of tracking data.

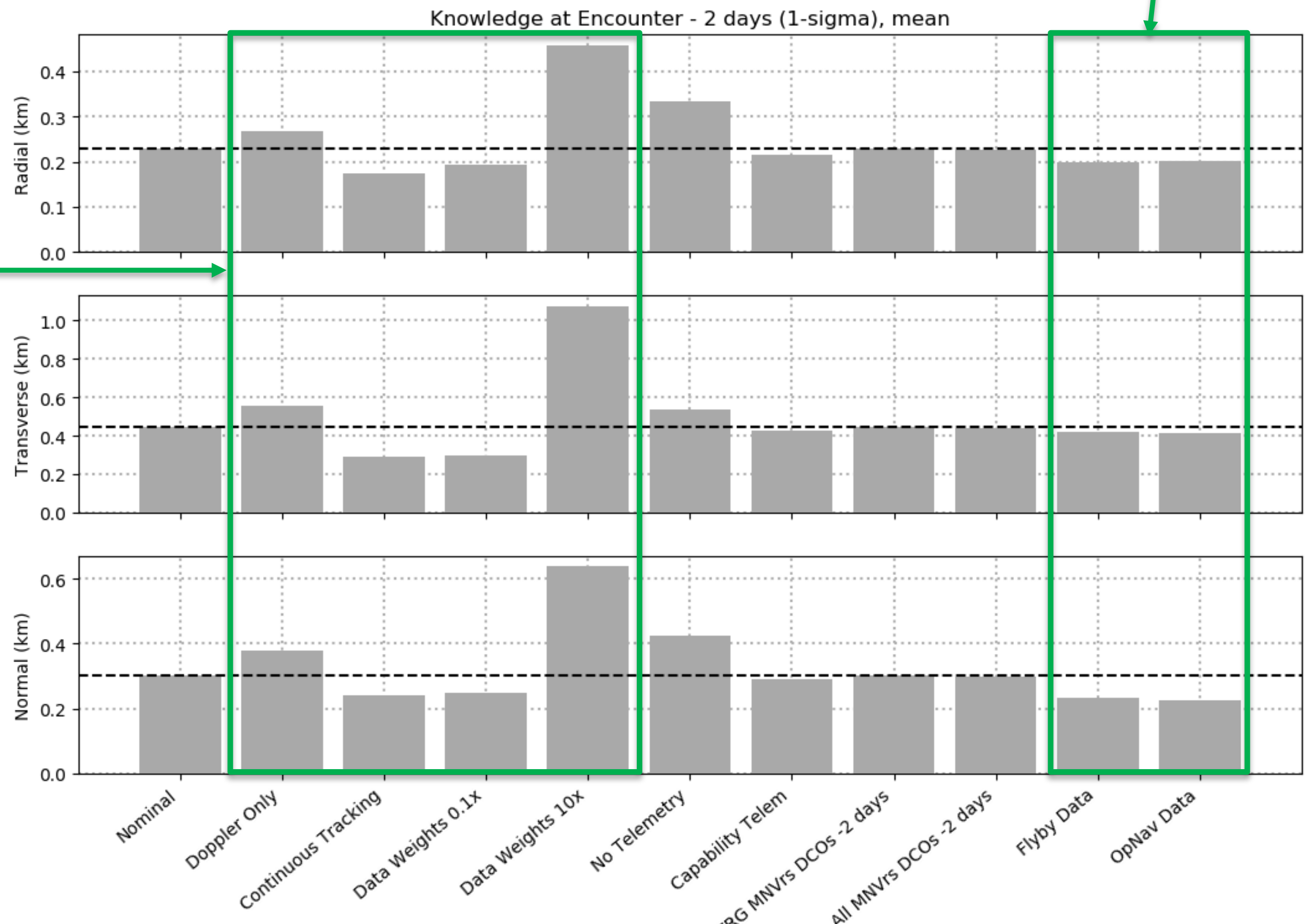


Mean Knowledge Uncertainties

Variations on Data Type and Amount

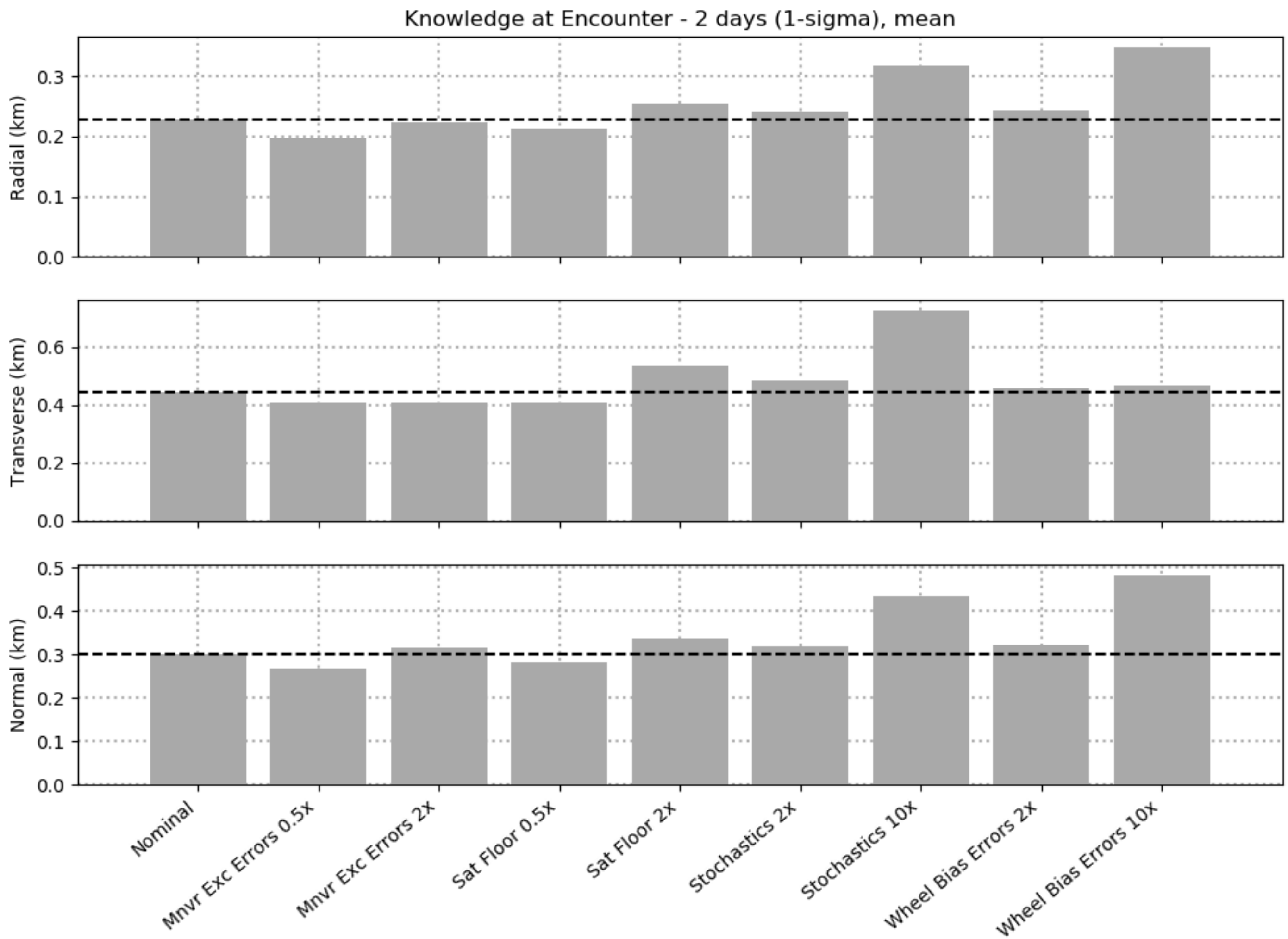
Some decrease in uncertainties with flyby and optical data.

Some sensitivity to quality and quantity of tracking data.



Mean Knowledge Uncertainties

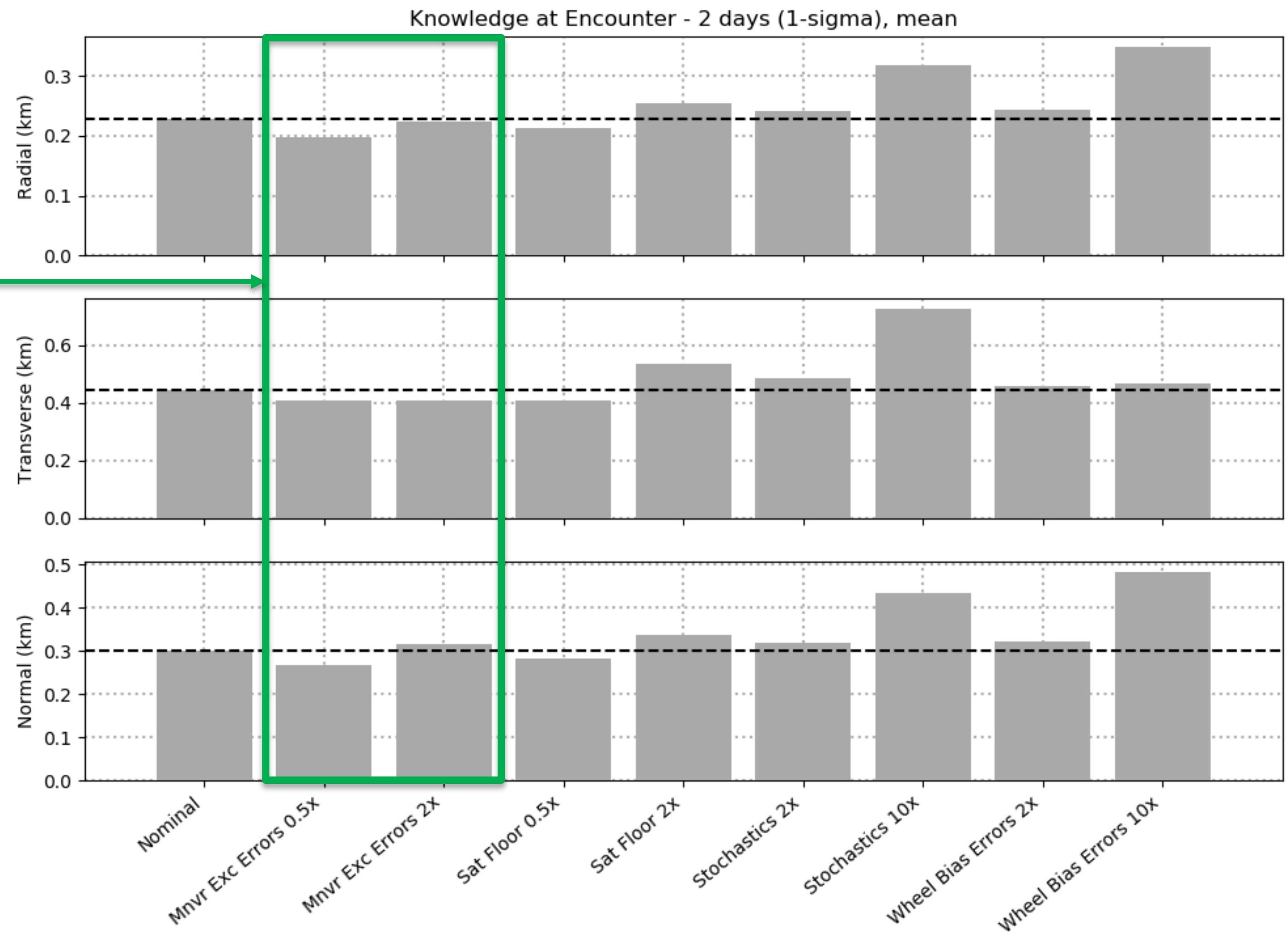
Variations on Dynamic Parameters



Mean Knowledge Uncertainties

Variations on Dynamic Parameters

Low sensitivity to maneuver execution errors

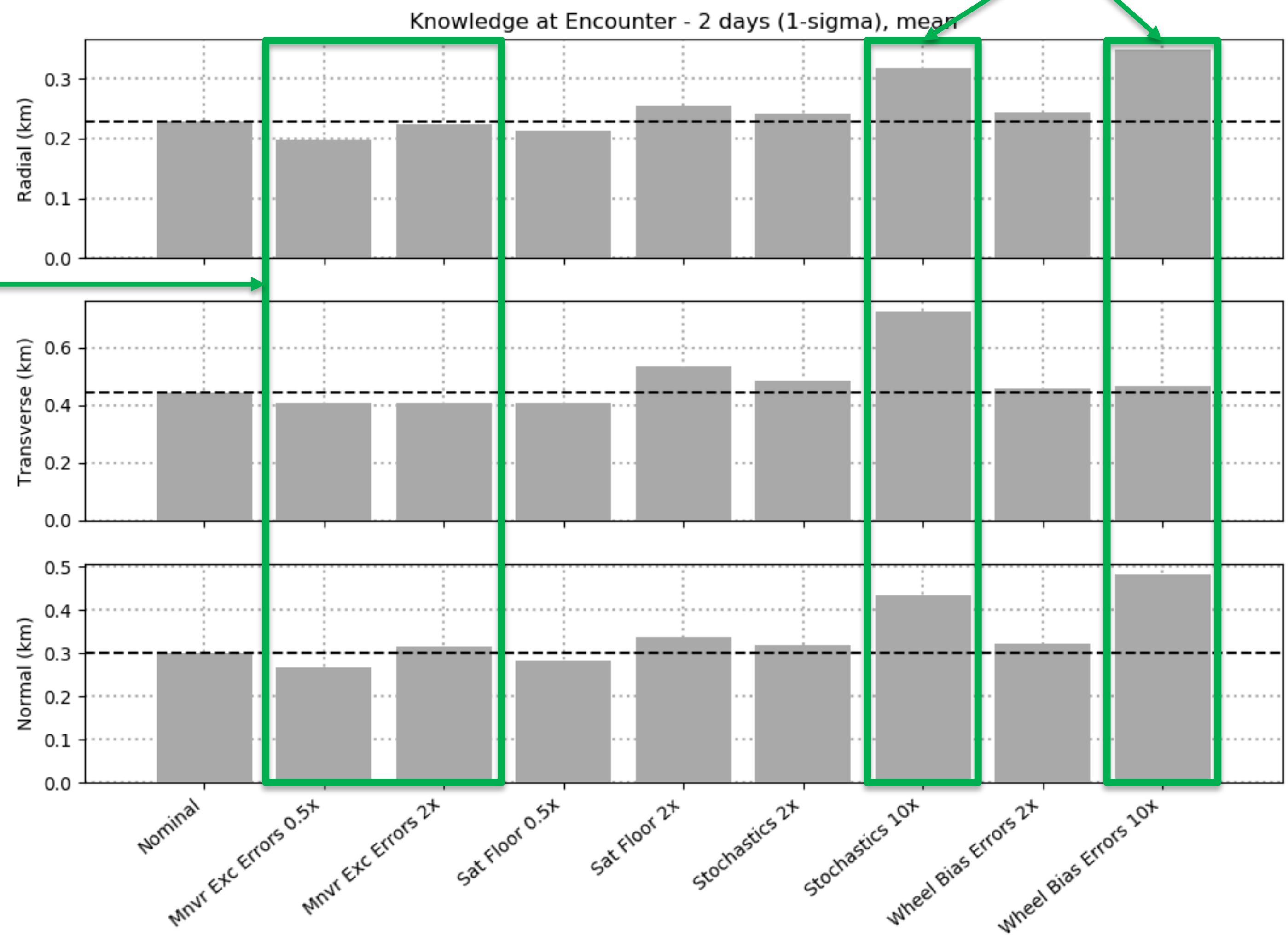


Mean Knowledge Uncertainties

Variations on Dynamic Parameters

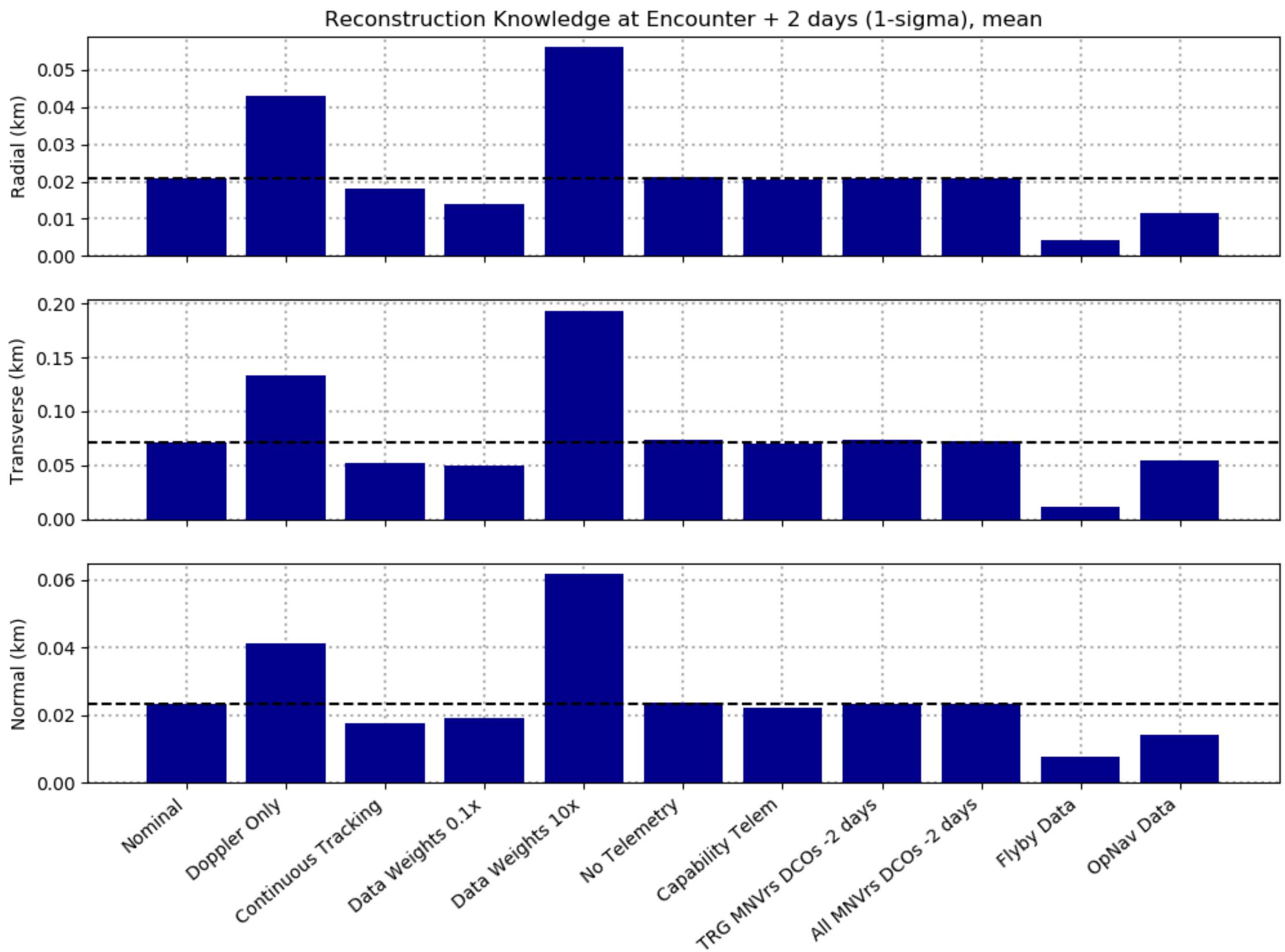
Some uncertainty growth from 10x increases in stochastic and wheel bias errors

Low sensitivity to maneuver execution errors



Mean Reconstruction Uncertainties

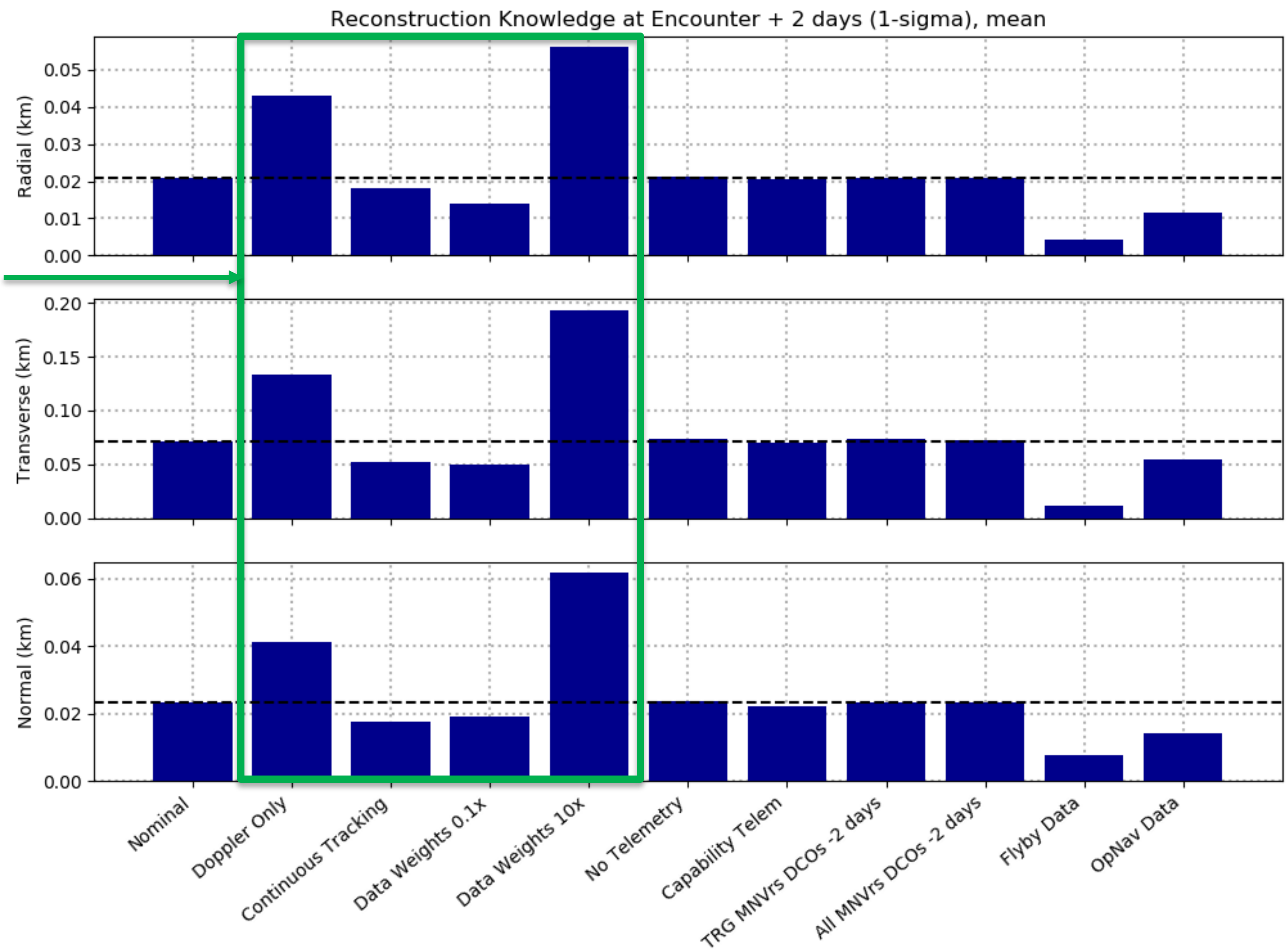
Variations on Data Type and Amount



Mean Reconstruction Uncertainties

Variations on Data Type and Amount

High sensitivity to quality and quantity of tracking data.

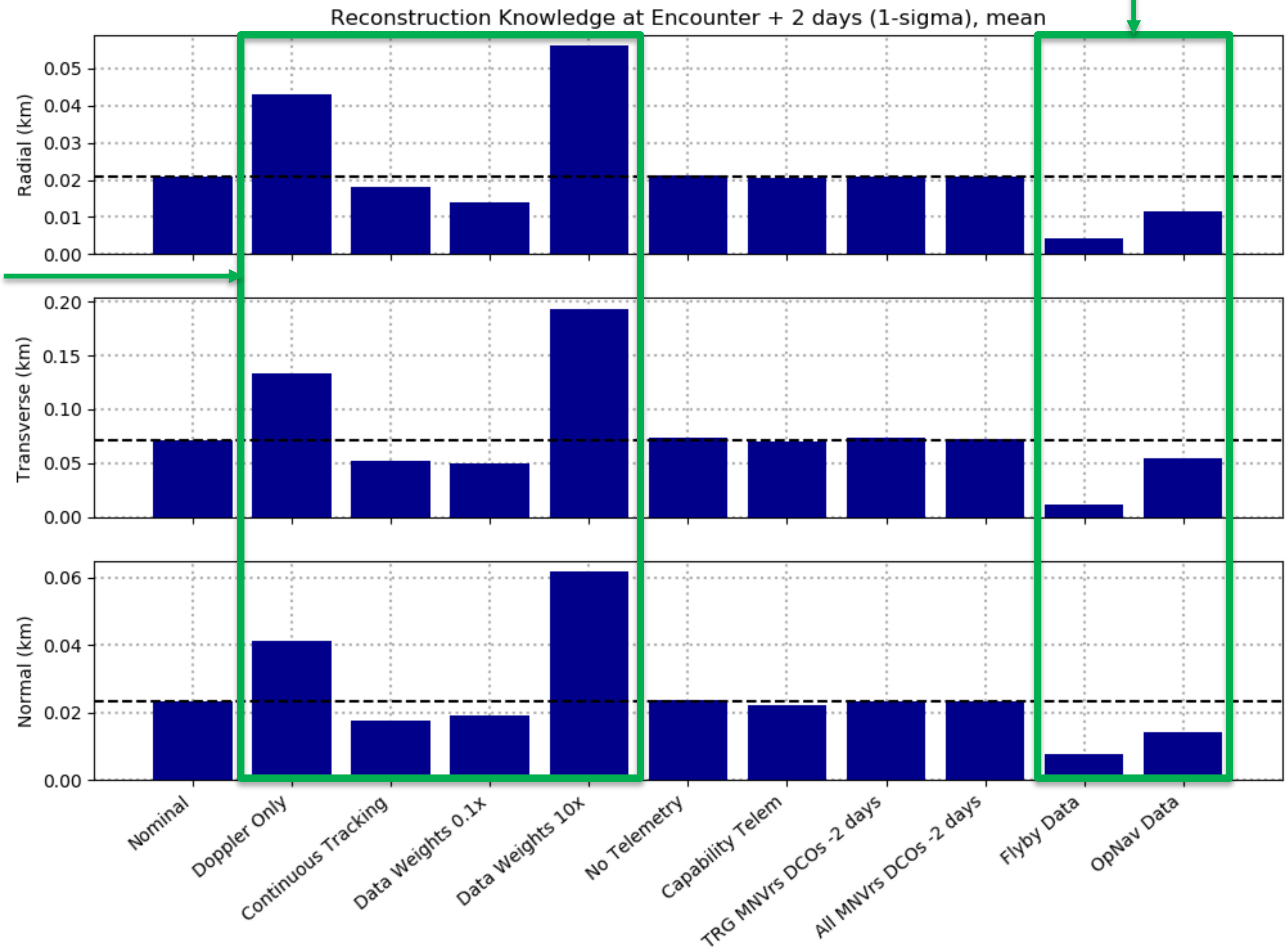


Mean Reconstruction Uncertainties

Variations on Data Type and Amount

Large reductions in uncertainty provided by optical data and even more from flyby data.

High sensitivity to quality and quantity of tracking data.



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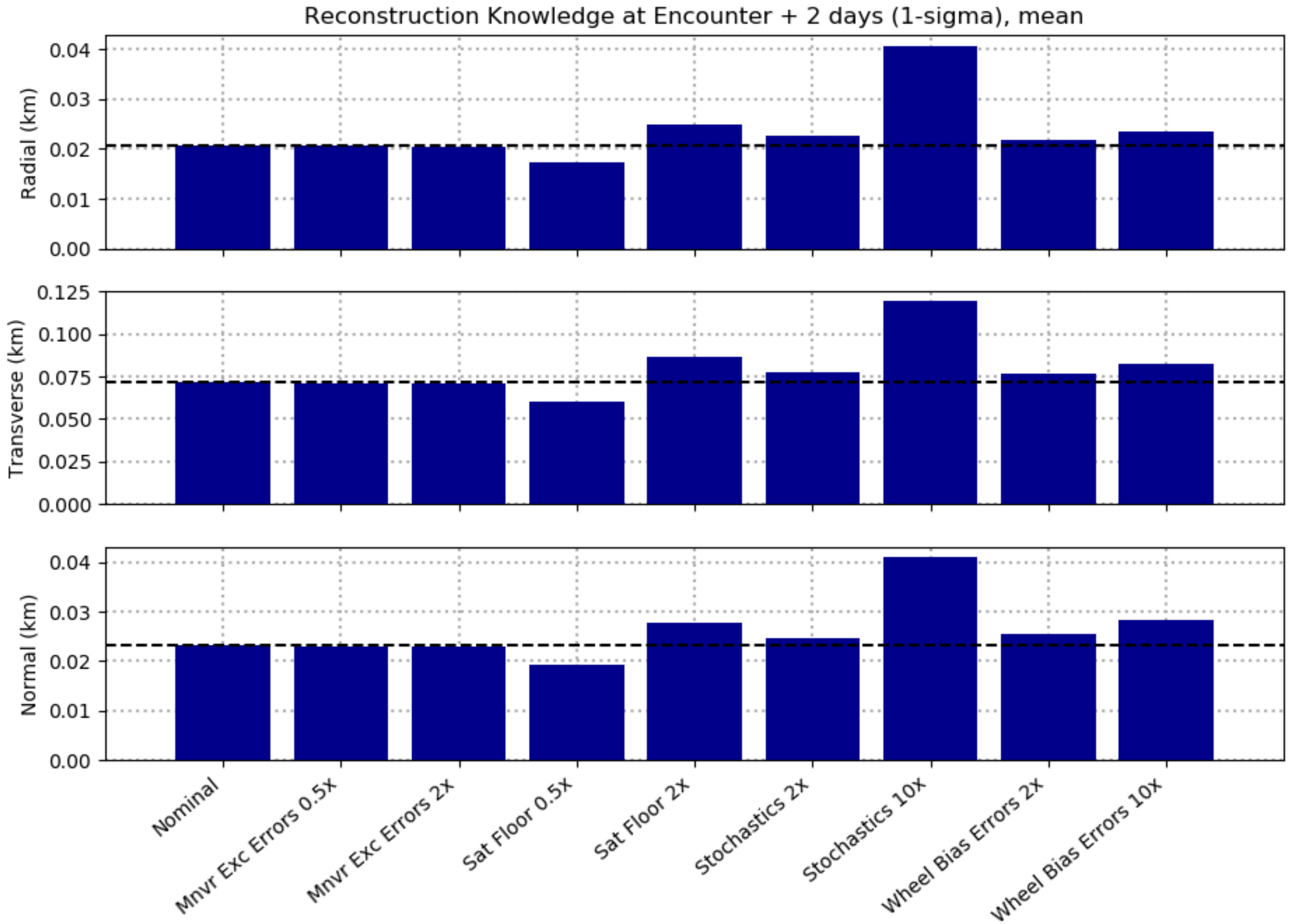
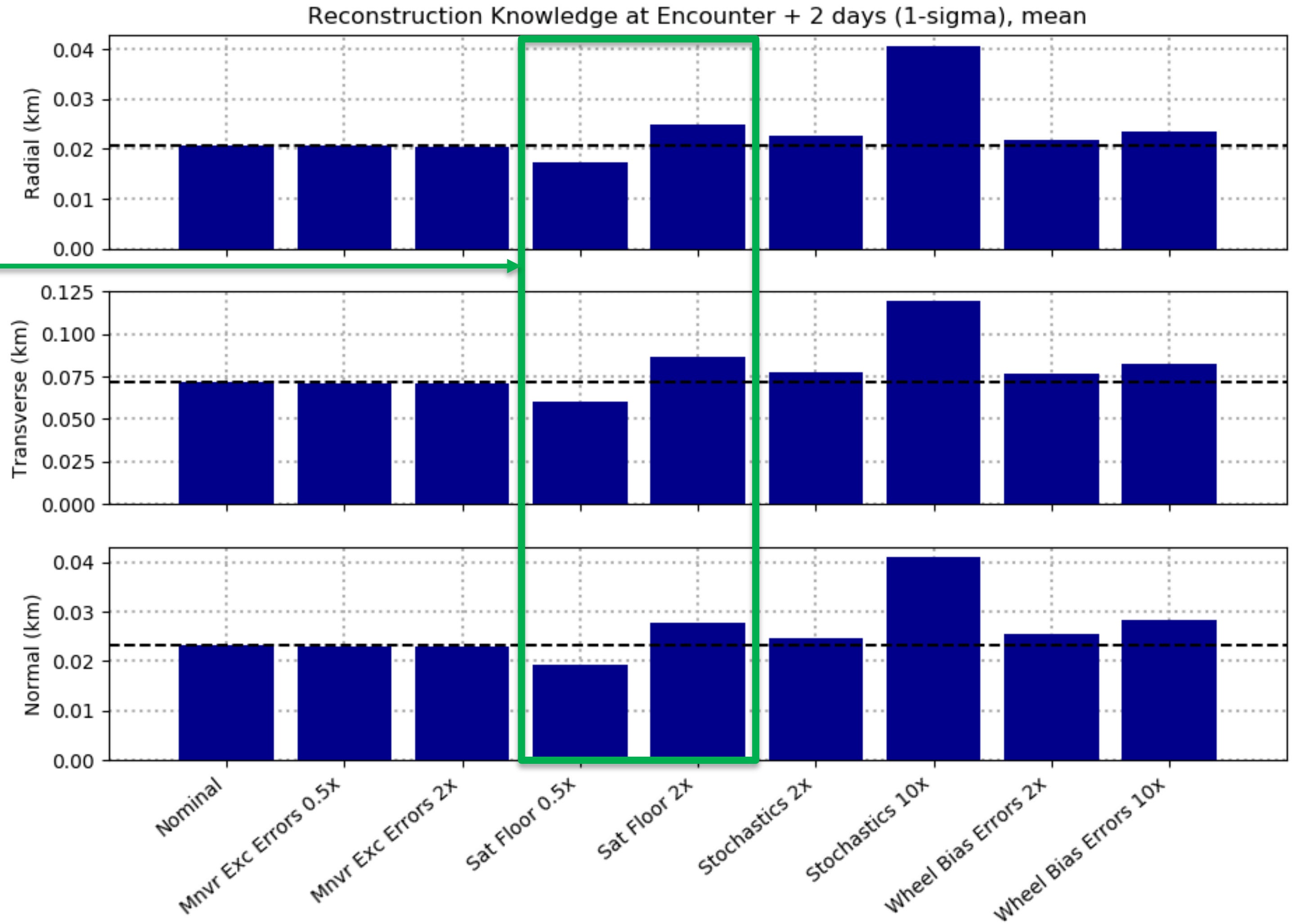


Mean Reconstruction Uncertainties

Variations on Dynamic Parameters

Some sensitivity to satellite ephemeris covariance

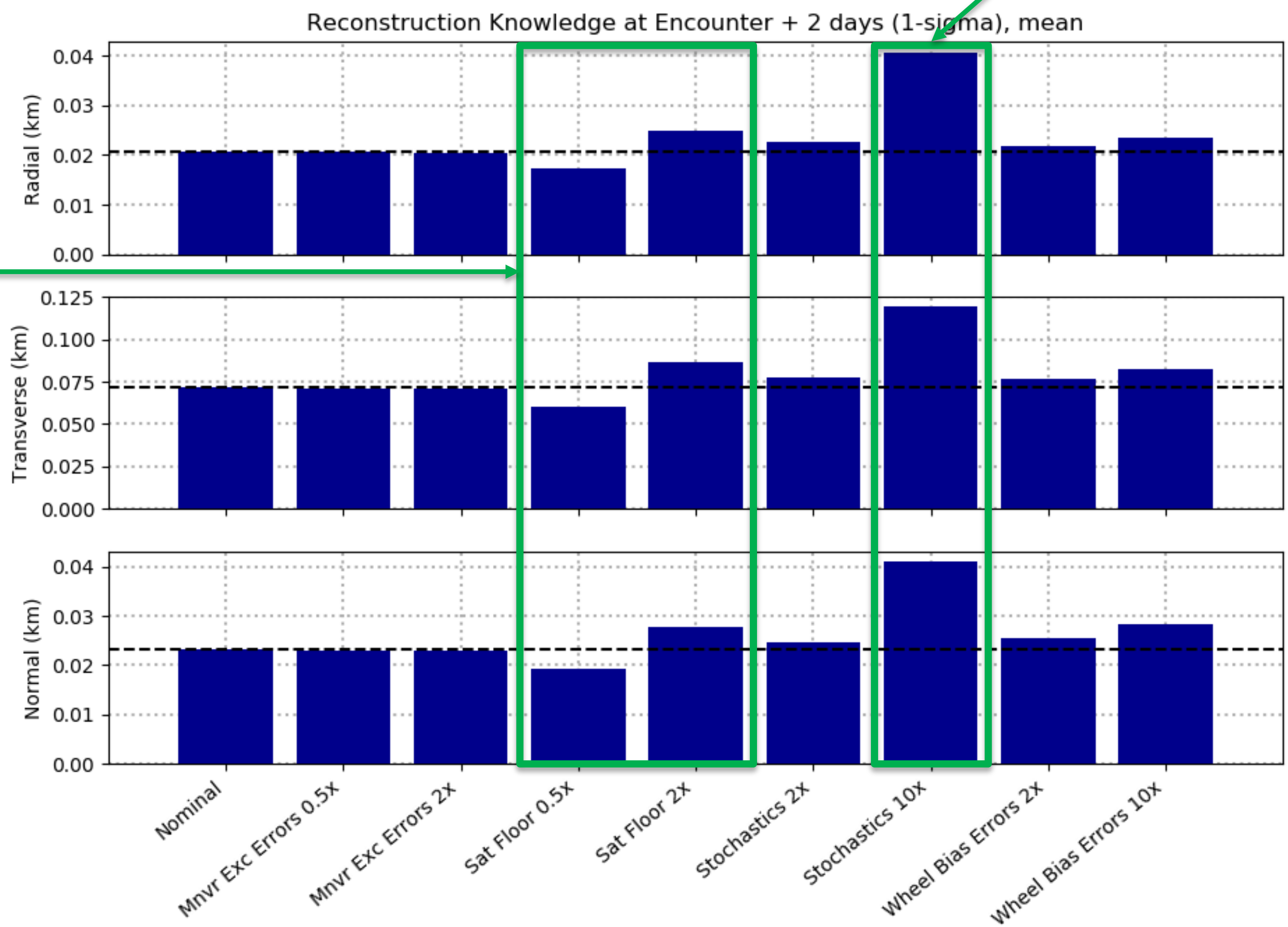


Mean Reconstruction Uncertainties

Variations on Dynamic Parameters

Sensitive to a large increase in stochastic errors

Some sensitivity to satellite ephemeris covariance



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Approach Maneuver Delivery

- Uncertainties largely insensitive to changes to data type and amount.
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- Improvements in the maneuver execution modeling would lead to the greatest improvement in OD delivery capability.

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- Large degradations to data quality or large data outages result in unacceptable increases to the uncertainty values, but are unlikely.
- The navigation baseline is robust to realistic increases to error sources.
- Acquiring maneuver pointing telemetry at the expected accuracy contributes significantly to lower knowledge uncertainties, and is clearly necessary to maintain acceptable uncertainty levels.
- Addition of optical data and radiometric flyby tracking data reduces uncertainties, especially for problem encounters.

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Encounter Reconstruction

- Uncertainties improve greatly with increased data near the encounter
- Utilization of optical data and radiometric flyby tracking are both very effective at improving reconstruction OD, especially for problem encounters. (True even in cases with degraded ephemeris knowledge)

Jet Propulsion Laboratory
California Institute of Technology